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Anti-disturbance Control For an Underwater Vehicle In Shallow Wavy Water

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Abstract

Attitude Control for an underwater vehicle working in shallow wavy water is an important capability. In shallow water this mission most likely will be disturbed by the large surge induced hydrodynamic forces acting on the underwater vehicle. In this paper, the second order wave drift force affecting severely the underwater vehicle in shallow water are presented. On the basis of wave force analysis, three dimension disturbances caused by wavy surgy water are measured and a control system using least squares multi-order data fitting polynomial prediction and fuzzy compensation combined with PID controller is put forward. The experimental results show that the control system for disturbance of surge and wave is feasible and effective.

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Keywords: underwater vehicle; shallow water; second order wave; control strategy

1. Introduction

The underwater vehicles are very suitable for the completion of underwater monitoring, detection, testing and other tasks. The underwater vehicles are almost active in the deep sea. Because of being quite

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in the deep sea, the sea wave doesn't affect the underwater vehicles seriously. However, in very shallow water the waves disturb the underwater vehicle severely. For an Underwater Vehicle to operate with a high degree of reliability, disturbances and their effects on the underwater vehicle should be modeled with an adequate degree of accuracy. The main sources of the dynamic disturbances encountered by underwater vehicles in shallow water are wave and current induced. These disturbance forces arise from buoyant and inertial effects due to wind, wave and fluid, especially the wave. The forces arise from the wave can be classified into two parts. One is the first order wave force which has the same frequency with the wave;it is caused by the waves which have high frequency and small amplitude. It is the source that causes the underwater vehicles' pitch motion. But it has small influence on the roll motion [1]. The other one is the second order wave drift force which is caused by the long cycle drift movement of the irregular wave. It is smaller comparing with the first order wave force, but it is the main source which causes the horizontal drift of the underwater robot, especially under the wave resonance circumstances. It can arouse a deal of additional stress [2]. So it is necessary to research on the second order wave drift force.

The underwater vehicles must keep attitude in order to complete task when working. However, the underwater vehicles will be impacted by the inevitable surge, which will result in errors in the attitude control, affecting their normal operation. Many control strategies have been developed for the underwater vehicles [3-7]. Some of these works are summarized in [8]. The work has been shown that the control overshoot must be suppressed in the ROV control system design [9].

In this paper, calculation and simulation of the second order wave are given. Then, anti-disturbance control strategy is put forward which is used in an underwater vehicle developed by Shanghai University, shown in Figure 1.

Figure 1. An underwater vehicle developed by Shanghai University

2. The calculation of the second order wave

The wave surface which can be described by simple function is defined as regular wave. The regular wave can present the flow and it is also the basic of reach on the irregular wave. The long wave can be described as a composition of so many single regular waves which are independent, have different wavelengths, different amplitudes and stochastic phase, so it can be described as

$$\zeta(t) = \sum_{i=1}^{\infty} \zeta_{ai} \cos(k_i x_0 - \omega_i t + \varepsilon_i) \tag{1}$$

Where, ζ is the distance that wave surface deviate from the water horizontal plane; x_0 is the coordinate of a point on the water horizontal plane; ζ_{ai}, $k_i, \omega_i, \varepsilon_i$ are amplitude, wave number, frequency, initial phase of the first order harmonics respectively. Learning from the wave theory, the phase ε_i distributes between 0 and 2π homogeneously and stochastically. Taking one certain point on the horizontal plane into consideration, we can neglect the higher order harmonics, so equation (1) can be simplified as follows:

$$\zeta(t) = \sum_{i=1}^{n} \zeta_{ai} \cos(\omega_i t + \varepsilon_i) \tag{2}$$

Which equation (1) and equation (2) are called Longuet-Higgins[4] wave model. From fluid mechanics knowledge, we can know the energy of a single harmonic in unit area can be described as

$$E = \frac{1}{2}\rho g \zeta_a^2 \tag{3}$$

Where ρ is water density; g is the acceleration of gravity. Make use of the superposition principle of wave, we can make a conclusion that the energy of stochastic wave which is between ω and $\omega + \Delta\omega$ can be shown as:

$$E = \frac{1}{2}\rho g \sum_{i=\omega}^{\omega+\Delta\omega} \zeta_{ai}^2 \tag{4}$$

Define a function $S_\zeta(\omega)$ to make the equation holds

$$\frac{1}{2}\rho g \sum_{i=\omega}^{\omega+\Delta\omega} \zeta_{ai}^2 = \rho g S_\zeta(\omega)\Delta\omega \tag{5}$$

From equation (5) we can know, $S_\zeta(\omega)$ is proportionate to the wave energy. So it can be called the density of the wave energy. When the $\Delta\omega$ is small enough, according to this equation we can identify the harmonics amplitude which frequency is in $\Delta\omega$ district as follows

$$\zeta_{ai} = \sqrt{2S_\zeta(\omega_i)\Delta\omega} \tag{6}$$

There are so many researches on the control of underwater vehicles motion, and the spectroscopy are used. Pierson-Moscowitz spectroscopy (PM spectroscopy)[5] is its basis.

$$S_\zeta(\omega) = \frac{A}{\omega^5}\exp(-B/\omega^4) \tag{7}$$

Here $A = 0.78, B = 3.11/H_{1/3}^2$, $H_{1/3}$ is significant wave height.

When the underwater robot navigates at certain velocity and direction, actual frequency of the wave on the vehicle is not the natural frequency, but the encountered frequency ω_e .

Supposing that the underwater vehicle navigates at the velocity of U , which encounters the angle β (the angle between the orientation of the wave propagation and the orientation of the underwater vehicle navigation) under this situation, the relationship between encountered frequency and natural frequency is

$$\omega_e = \omega - \frac{\omega^2}{g} U \cos\beta \tag{8}$$

In accordance with principle of energy equivalence, when the energy of slight area under the natural frequency converts to the energy of slight area under the encountered frequency, the energy doesn't change. So there is a equation that

$$S_\zeta(\omega)d\omega = S_\zeta(\omega_e)d\omega_e \tag{9}$$

From (9), we can get

$$S_\zeta(\omega_e) = S_\zeta(\omega) \Big/ (1 - \frac{2\omega}{g} U \cos\beta) \tag{10}$$

3. The simulative and experimental data of the second order wave

3.1. The simulation of the second order wave

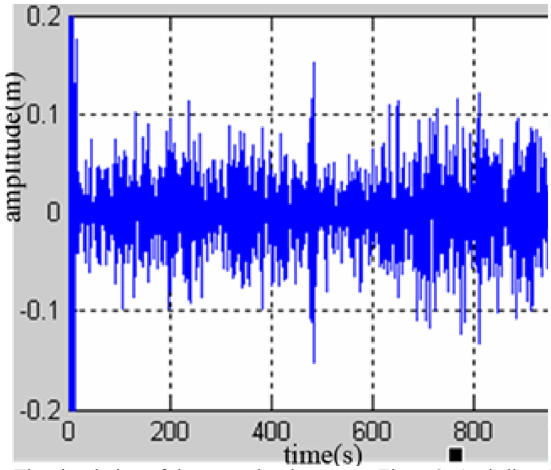
When simulating the second order wave, we should make sure the wave parameter (such as significant wave height) and related parameter of underwater vehicles navigation (such as the velocity, the encountering angle). Here we define $H = 0.8, U = 5, \beta = 90^\circ, \omega_1 = 0.12, \omega_2 = 0.98, t = 1:1:1500$.

Then, We discretize the wave. There are many discrete methods, so we use equal intervening time method. As all the wave spectrometers are narrow so their energy is mainly in some frequency phase. We can choose finite spectrometers which frequency is in the certain frequency phase to do simulation. Suppose the simulation frequency phase is from ω_1 to ω_n , divide to 'N' portions, so the frequency increment $\Delta\omega = \frac{\omega_n - \omega_1}{n}$ .Refer to equation (6) we can define certain spectrometer amplitude ζ_i under certain frequency ω_i .

Superpositing the spectrometer one by one refer to equation (3) we can get the wave simulation. The initial phase angle of each spectrometer ε_i can be generated by a random program from 0 to 1. If the wave has the encounter frequency, the simulation can be got from the formula:

$$\zeta(t) = \sum_{i=1}^{n} \sqrt{2S_{\zeta}(\omega_i)\Delta\omega_i} \cos(\omega_{ei} t + \varepsilon_i) \tag{11}$$

Use MATLAB software to write programs, we get the simulation curve. The figure 2 shows the results of the simulation of the second order wave. The “x-axis” means time and the “y-axis” means the amplitude. we can see the amplitude trend with the time. It support the argument that the long wave can be described as a composition of so many single regular waves which have different independent wavelengths, amplitudes and stochastic phases.



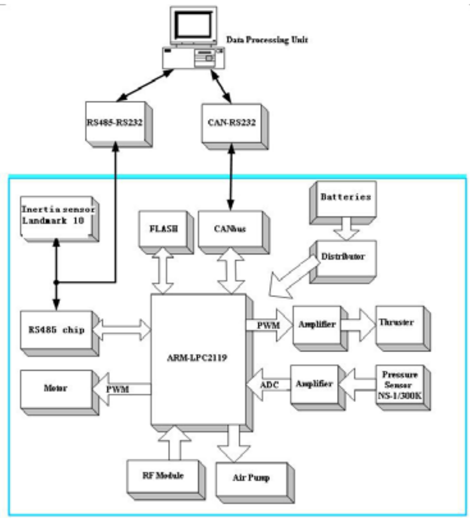


Figure 2. The simulation of the second order wave ; Figure3. Anti-disturbance experimental platform

3.2. The experimental data of the second order wave

Anti-disturbance experimental platform is shown in Figure3.

Double RS485 buses are adopted between underwater vehicle and data processing unit. Philip ARM LPC2119 is adopted as controller. Control system of vehicle includes inertia navigation LandMark10AHRS, depth sense system, RF module, driving system.

We did the experiments of surge for underwater vehicle in the wavy pond in Baoshan campus of Shanghai University. Experimental data of the second order wave are given in the Figure 4.

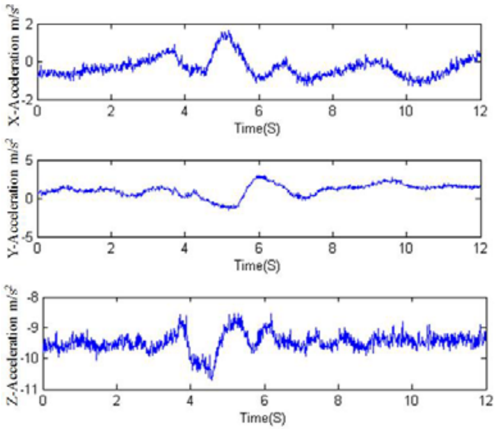


Figure 4. Experimental data of the second order wave

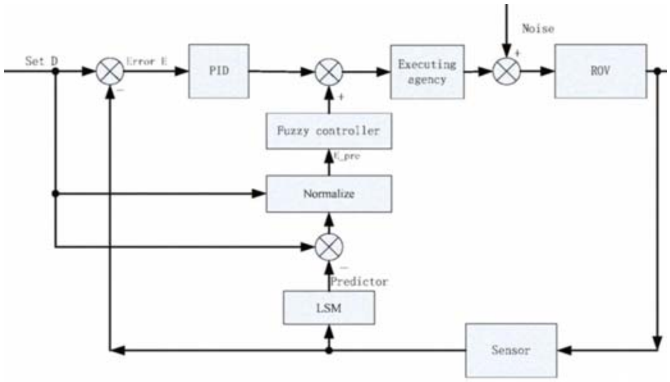


Figure 5. Anti-disturbance control strategy

4. Anti-disturbance control strategy

Anti-disturbance control strategy for an underwater vehicle is shown in figure5. As shown, this method processes the multi-order data fitting by least square method and generates the nonlinear predictor by the multi-order fitting function. Then the predicted error is normalized as the input of the fuzzy controller. The fuzzy controller generates the lead compensates to the control value by fuzzy rules. Finally, the system uses PID control method in main control channel and fuzzy nonlinear compensation control method in the feedback forward channel to achieve the whole control system.

The result of anti-disturbance control for an underwater vehicle is shown in Figure 6. By comparing between Figure 4, experimental data of the second order wave and Figure 6, the result of anti-disturbance control, fluctuations of accelerations in the direction of X,Y,Z are suppressed to low-amplitude, respectively before 12 seconds. However, fluctuation amplitudes of accelerations in the direction of X,Y are still ±2m/s2 after 25seconds. These are results of more turbulent waves around the vehicle after 25 seconds.

On the other hand , fluctuation of acceleration in the direction of Z is suppressed to low-amplitude all the time. The result of anti-disturbance control indicates that Anti-disturbance control strategy developed in this paper is valid but limit to suppress the fluctuation of underwater vehicle.

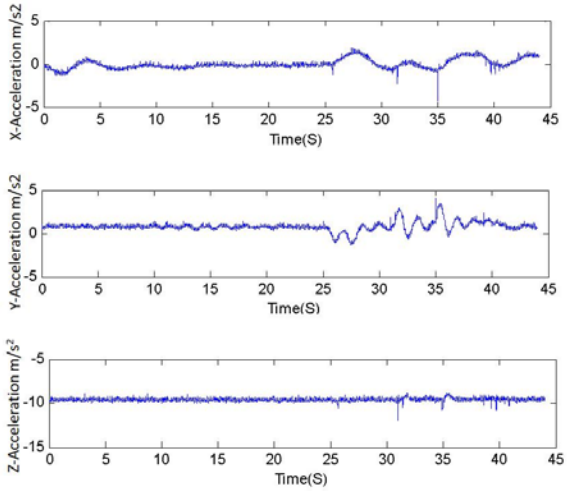


Figure 6 The result of anti-disturbance control

5. Conclusions

This paper presents calculation and simulation of the second order wave and the anti-disturbance control strategy based on least squares multi-order data fitting polynomial prediction and fuzzy compensation combined with PID controller for an underwater vehicle. The experimental results show that the control system for disturbance of surge and wave is feasible and effective.

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